

CMS engagement in Hadron Spectroscopy (RF07)

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(on behalf of the CMS Collaboration's B-Physics Analysis Group)

SNOWMASS 2021
Rare Processes and Precision Frontier Townhall meeting
October 2nd 2020

<https://indico.fnal.gov/event/45713/sessions/16422/#20201002>

CMS Letter-of-Interest @ Snowmass21

The CMS Collaboration has submitted an overall LoI:

https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF1_EF10-RF5_RF7_CMSCollaboration-109.pdf

In this Letter, one can find a well-structured physics program and a wide spectrum of proposed measurements for the High-Luminosity LHC (HL-LHC or Phase-II);

- for some topics, some projection studies have been already performed**
- for others, they are foreseen**

Letter of Interest
The CMS Collaboration contribution to Snowmass 2021

CMS Collaboration

August 27, 2020

[...]

List of expected topics.

Public results are given with citations, new or modified analyses are indicated in italic font.

Activities related to the RF07 subgroup are mentioned in the LoI as follows:

[...]

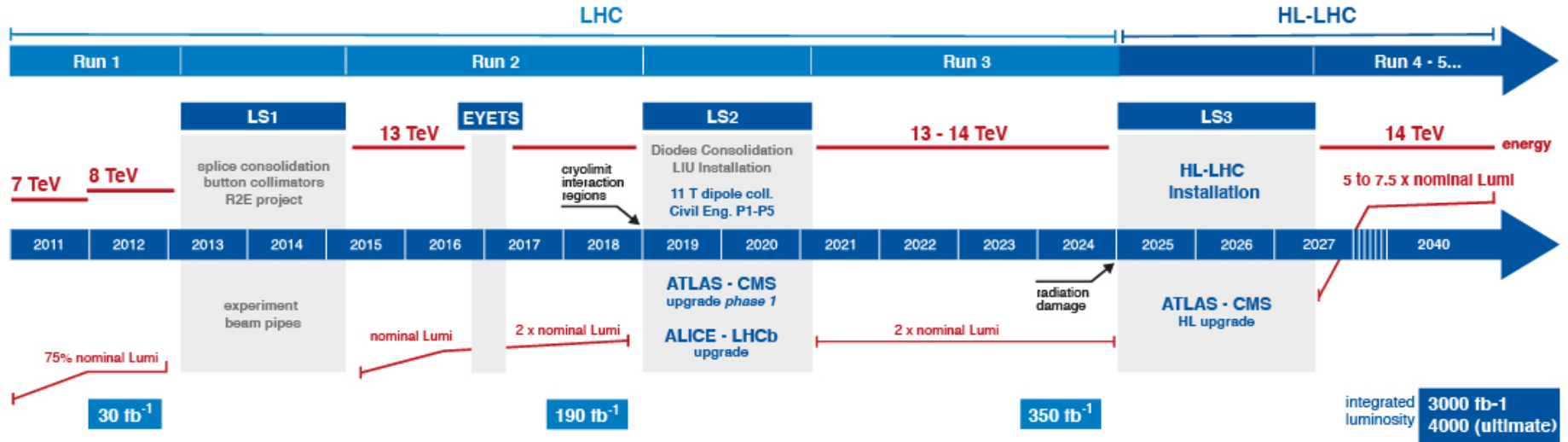
Precision measurements of top quark properties present an important test of the SM. As the heaviest particle in the SM, the top quark plays an important role in the electroweak symmetry breaking and is a sensitive probe for physics beyond the SM. The flavor physics program at the HL-LHC comprises many different probes with significant discovery potential. The heavy flavor and top quark-related topics will be presented in **EF03**. Rare decays of tau leptons will contribute to **RF05**. A few selected analyses can contribute to the future conventional and exotic Hadron Spectroscopy program in **RF07**.

[...]

RF07: Hadron Spectroscopy

1. *Precision studies of production of heavy mesons and baryons*
2. *Searches of exotic heavy hadronic states*

Run-3 & Phase-II (HL-LHC) scenario



Run-3 target (2022-2024): ~double the statistics collected so far

Phase-II /HL-LHC (from 2027): increase the statistics by a factor ~10 (i.e. 3-4ab⁻¹)

Plan to access rare SM processes & perform precision measurements in the Flavour sector.

Heavy Flavour potential (based on low-pT signatures) will suffer from the HL-LHC pileup conditions ($\langle \text{PU} \rangle \sim 140-200$)

Availability of **tracking information at L1-trigger** is crucial to retain the full physics potential in this harsh environment

CMS Phase-II Upgrade (overview)

CMS Phase-II upgrades include:

- a new tracker with improved p_T resolution and radiation hardness, lower material budget, extended coverage
- increased muon coverage
- a new forward calorimeter with high granularity and resolution
- addition of the MIP timing detector (MTD)
- increased trigger bandwidth & latencies
- inclusion of tracking information at L1 trigger
- replacement of electronics

Trigger/HLT/DAQ

- Track information in hardware event selection
- 750 kHz hardware event selection
- 7.5 kHz events registered
- latency increased from 3.2 to 12.5 μ s

Barrel EM Calorimeter

- New electronics
- Low operating temperature = 10°

Muon systems

- New DT & CSC electronics
- New chambers in $1.6 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$

MIP timing detector

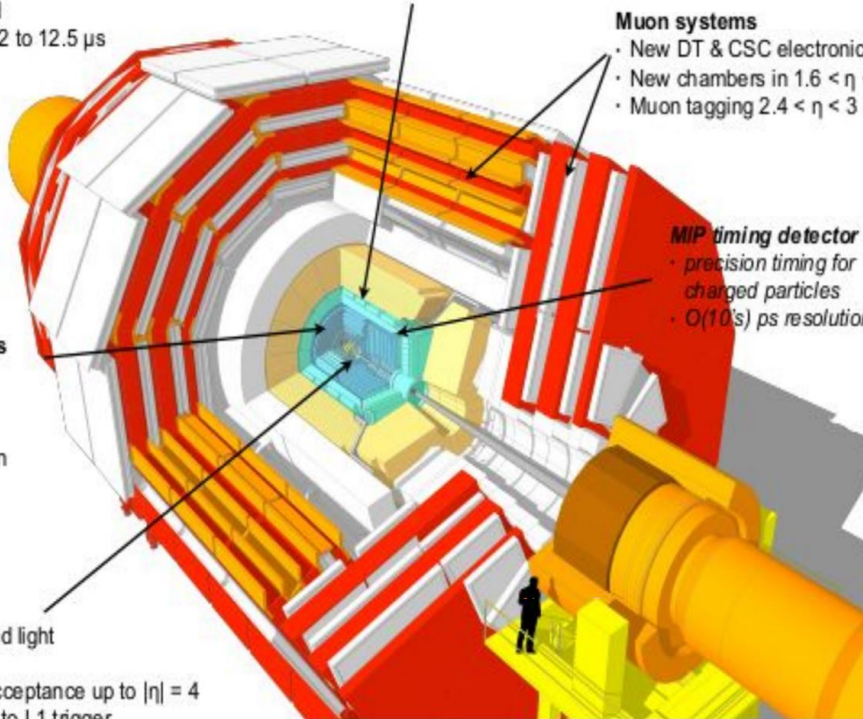
- precision timing for charged particles
- $O(10's)$ ps resolution

New endcap calorimeters

- Sampling calorimeter
- Radiation tolerant
- High granularity
- 3D shower reconstruction

New tracker

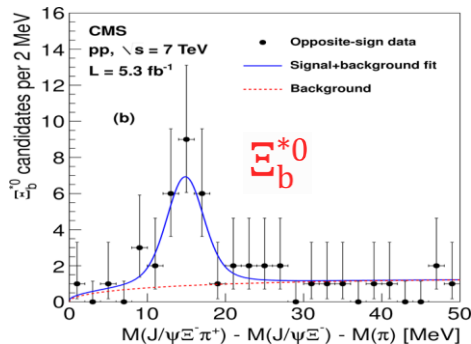
- Radiation tolerant and light
- Higher granularity
- Increased forward acceptance up to $|\eta| = 4$
- Tracking information to L1 trigger



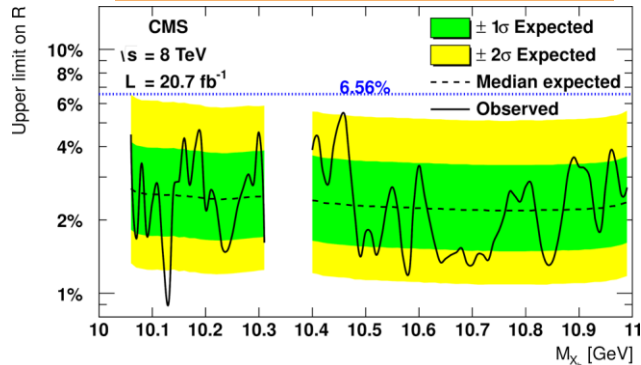
Physics capabilities in hadron spectroscopy (from the past ...)

Here is a selected collection of plots testifying to a few achievements in spectroscopy: searches for new hadron states

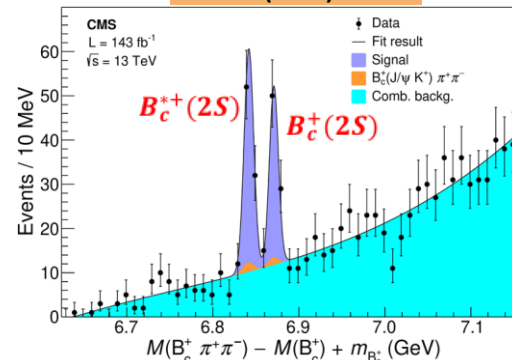
PRL 108 (2012) 252002



PLB 727 (2013) 57 Search for $X_b \rightarrow \Upsilon(1S)\pi\pi$

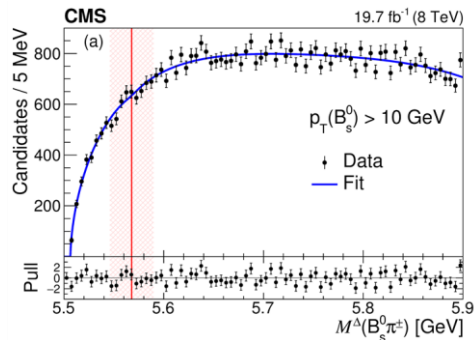


PRL 122 (2019) 132001

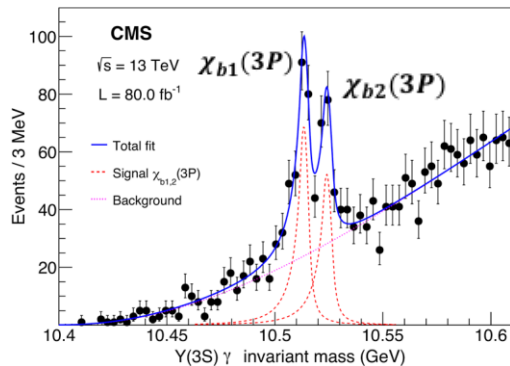


PRL 120 (2018) 202005

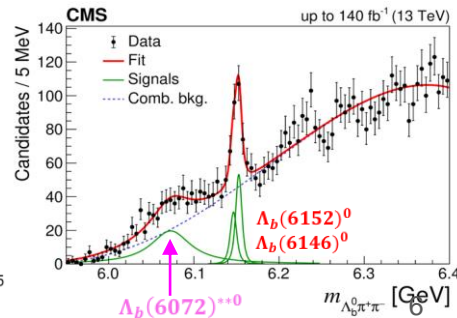
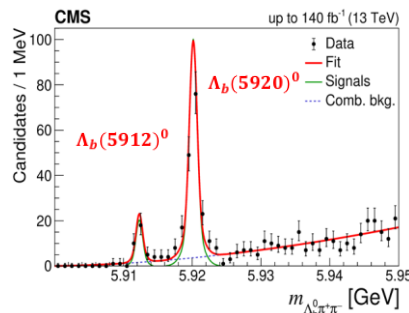
Search for $X(5568)$



PRL 121 (2018) 092002



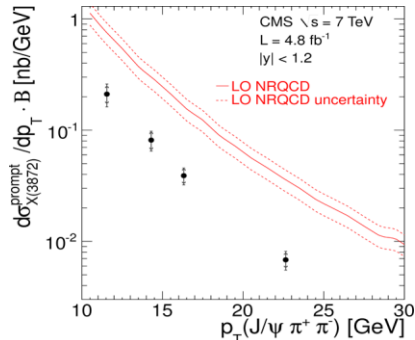
PLB 803 (2020) 135345



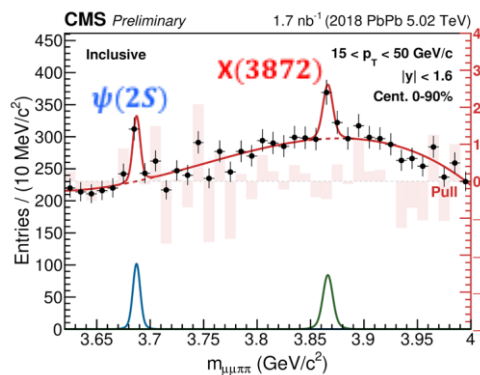
Physics capabilities in hadron spectroscopy (from the past ...)

Also a few achievements in the observation of new decay modes and studies of exotic states:

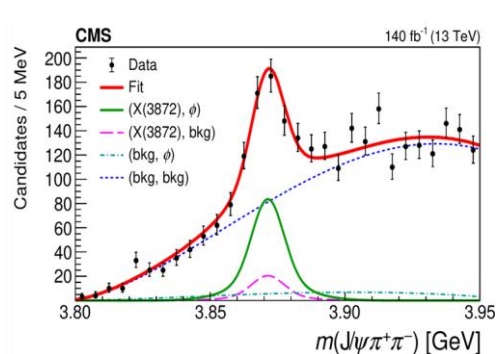
JHEP 04 (2013) 154 Prompt X(3872)



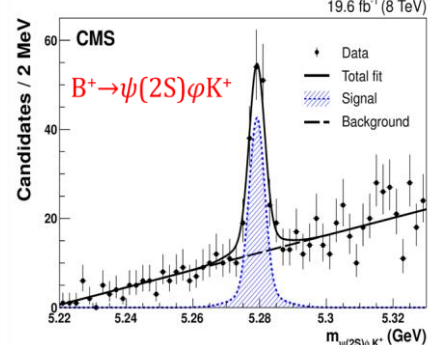
CMS PAS HIN-19-005 X(3872) in PbPb



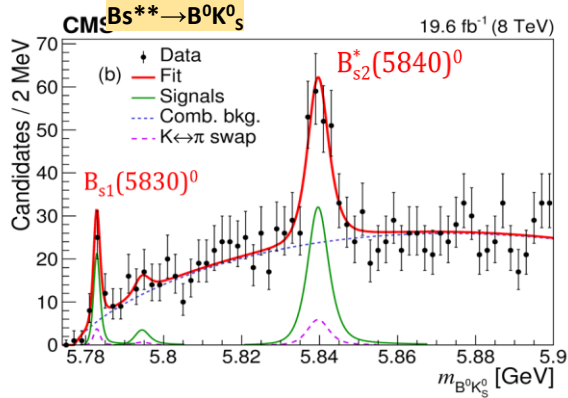
arXiv:2005.04764 (PRL) Observ. of $B_s \rightarrow X(3872)\phi$



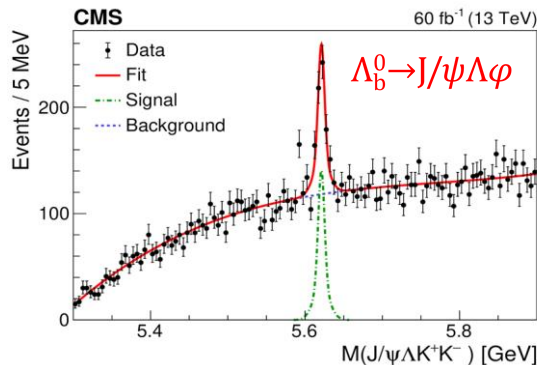
PLB 764 (2017) 66



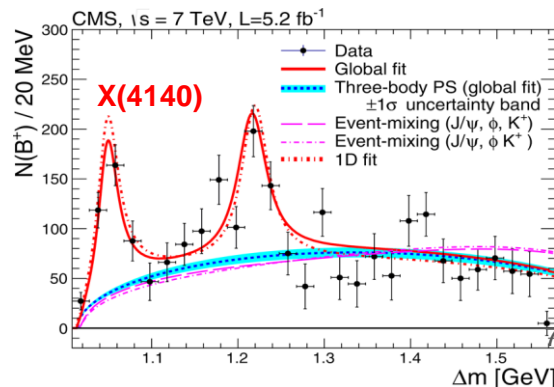
EPJC 78 (2018) 939



PLB 802 (2020) 135203



PLB 734 (2014) 261 J/psi phi from B+ to J/psi phi K+



Physics capabilities in hadron spectroscopy (... to the future)

- “Standard” triggers will record large amounts of well-reconstructed b-hadrons in charmonium decay modes, as well as charmonium and bottomonium states.
 - Smart compromise between available trigger rate and kinematic threshold under investigation for Run-3 and beyond
 - High Level Trigger budget rate limit will require clever selection and prioritization to target all signal topologies of interest
- B hadron & quarkonia production measurements in a phase-space complementary to LHCb (pp) and ALICE (HI collisions).
- Double-charmonia and double-bottomonia measurements and searches can be carried out at the same or better sensitivity compared to LHCb, thanks to excellent CMS muons’ acceptance.
- QCD exotics in HI collisions (X(3872) and beyond), hardly doable at ALICE.
- Beauty hadrons rare decays (observations, Branching Fractions); precision measurements for less rare decays (mass/lifetime/BF).
- New and improved measurements can be done in b/c/bc hadron + track(s) final states (B_c spectroscopy, doubly heavy baryons, ...)
- By using converted photons, where CMS is very precise and competitive, we can also study radiative transitions in relevant spectra.
- Very rare radiative decays, when resolution is not crucial, can be searched exploring the usage of calorimeter photons.
- The new additional timing layer (MTD) will allow:
 - hadronic PID capability for charged tracks with $p_T < 2\text{GeV}$
 - 3D vertex fit can be upgraded to a 4D (PU mitigation): precision timing for charged hadrons & converted photons

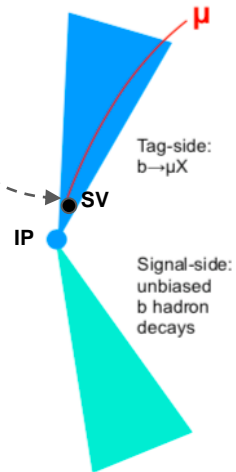
Additional physics capabilities (from present to future)

- The B-physics parking campaign has recorded $\sim 10^{10}$ **unbiased decays of beauty hadron** during the Run-2018 **exploiting the flexibility of CMS data taking model** (as luminosity drops in the fill the L1 rate is kept \sim constant & the HLT rate increased towards the end of each fill). **Trigger/tag-side requires a muon coming from a displaced vertex**

We finished to reconstruct these 12B events at the end of 2019

[<http://cds.cern.ch/record/2704495>] and we have on tape:

Mode	N_{2018}	f_B
Generic b hadrons		
B_d^0	4.0×10^9	0.4
B^\pm	4.0×10^9	0.4
B_s	1.2×10^9	0.1
b baryons	1.2×10^9	0.1
B_c	1.0×10^7	0.001
Total	1.0×10^{10}	1.0



- B-parked data set opens several prospects for spectroscopy studies**; its potentiality is still being studied.
- The possibility to continue B-parking efforts in Run-3 is currently under discussion
- Further **spectroscopy in charm sector** can be carried out utilizing semileptonic decays; charmed hadrons can be produced :
 - either at *tag side* ($b \rightarrow c \mu \nu$)
 - and at *probe side* (when $c \rightarrow s \mu \nu$ at *tag side*)

Work effort in RF07 & expected outcome from Snowmass process

From the point of view of your proposal, what would you like to come out of the Snowmass process?

- **Better understanding of the CMS capabilities in the hadron spectroscopy area towards the HL-LHC era, after completing few specific feasibility studies** in preparation for the July 2021 Snowmass meeting:
 - few of these studies may enter the RF07 contribution to the White Paper
 - we would favour the joint collaboration within RF07 group on topics where our contribution can be relevant
- **More highlighting of the physics potential** of this area of Heavy Flavor Physics within CMS, and therefore increased effort on improving and optimizing the new detector and in particular the design of triggering capabilities in order to explore this potential further.
- **Continuation of the strong U.S. support to the Phase-I and Phase-II LHC upgrade program.**

Summary

- CMS has proven to be one of the leading experiments in the hadron spectroscopy
- Many new and important results have been obtained using the data collected at the LHC Run-1 and Run-2, and more are coming
 - Particular strengths of CMS are photon conversions, large muons' acceptance, good reconstruction efficiency for low-momentum tracks (and K_s^0 , Λ)
 - Trigger design in Run-3 and beyond will be crucial
- The B-parking data set collected in 2018 may provide opportunities for spectroscopy studies not accessible with data collected by “standard” trigger algorithms. It may be planned again in Run-3.
- The additional timing layer (MTD) will allow for 4D track/vertex fits, precision timing for converted photons and charged hadrons (also allowing for hadron PID at low momenta).
- The U.S. Groups are important participants both in the CMS detector upgrades and within the CMS B-Physics program, and we are looking forward to **the continuation of the strong U.S. support to the Phase-I and Phase-II detector upgrades and Physics program.**